Fiber Reinforcement Architectures of PMCs on the Hygrothermal-Mechanical Performance for Aeropropulsion Applications

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ABSTRACT

A rigid lightweight sandwich support structure, for the combustor chamber of a new generation liquid propellant rocket engine, was designed and fabricated using PMC facesheet on a Ti honeycomb or Carbon foam core. The facesheet consisted of high stiffness carbon fiber, M40JB, and high temperature Polyimides, such as PMR-II-50 and HFPE-II. Six different fiber architectures; 4HS woven fabric, uni-fabric, woven-uni hybrid, stitched woven fabric, stitched uni-fabric and tri-axial braided structures have been investigated for optimum stiffness-thickness-weight-performance design criteria for the hygrothermal-mechanical propulsion service exposure conditions including rapid heating up to 200°F/sec, maximum operating temperature of 600°F, internal pressure up to 100psi.

An extensive property and performance database including dry-wet mechanical properties at both 25°F and 600°F in various loading modes, thermal and physical properties including blistering onset condition was developed for fiber architecture down-selection and design guidelines. Various optimized process methods including vacuum bag compression molding, solvent assistant RTM (SaRTM), resin film infusion (RFI) were utilized for PMC panel fabrication depending on the architecture type. In the case of stitched woven fabric architecture, the optimal stitch pattern was chosen in terms of stitch density and yarn size, based on both in-plane mechanical properties and blistering performance. Potential reduction of the in-plane properties transverse to the line of stitching was also evaluated. Attempt to correlate the experimental results with theoretical micro-mechanics predictions will be presented.

Subject Matter

- Parent HOTPC Program
  - Technical Program Overview & Strategies
- Fiber Architecture Studies
  - Objectives and Work Plans
  - Materials and Processing
  - Current Status and Results
    - Stitching Optimization/Evaluation
    - Composite properties/performance
- Summary and Conclusion
- Continuing Work Plans

HOTPC Program Synopsis

Objective:

Evaluate and develop carbon fiber reinforced high temperature polymer matrix composite (PMC) materials and fabrication technology suitable for manifolds, thrust chamber backup supports & attachments or turbo-pump housings in a new generation rocket engine.

Values:

- Significant weight reduction by replacing metal/ceramic components with PMC
- Increased thrust-to-weight ratio, reduced fuel consumption, thus cost saving
- Utilization of current enabling technologies in materials, design, process and fabrication areas, i.e., high feasibility!

Challenge:

- Needed high thrust-to-weight ratio (>30:1) that must be achieved to make this a viable flight propulsion system. By component weight reductions up to 25-30%,
- Required high stiffness (less than 0.05" deflection in a 12"×12" panel) and high temperature capabilities up to 600°F,
- Required good hygro-thermal stability especially under rapid heat-up exposure up to 200°F/sec

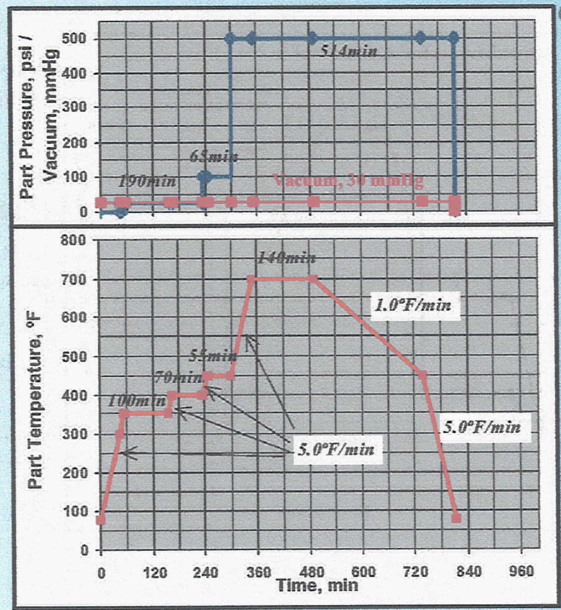
FIBER ARCHITECTURE: PROCESSING

PMR-II-50 resin w/ ~50% Monomer Solid

- Uni-tape; 4HS Woven; their Hybrid Composite Panels

Commercial Fabrics
⇓
Solution Prepregging
⇓
Hand Laying-up;

B--Staging @ 400°F for 1 hr in a metal mold w/ dead weight; Vac-Bagging



C-scan

Drying

Post Cure Cycle

- RT to 450°F in 2h, hold for 1 hr;
- 450 to 550°F in 2 h, hold for 1h;
- 550 to 600°F in 2 h, hold for 2;
- 600 to 700°F in 2h, hold for 16 h;
- Cool to RT in Oven (for 4 hrs)

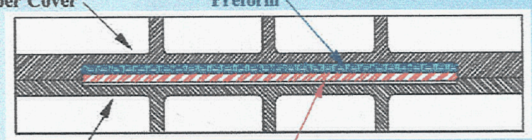
C-scan

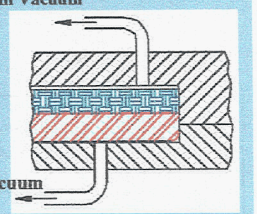
FIBER ARCHITECTURE: PROCESSING

PMR-II-50 resin w/ 66% Monomer Solid

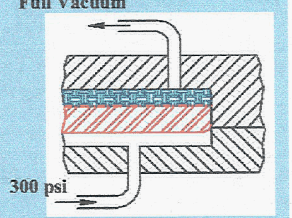
- Triaxial Braid; Stitched Woven Composite Panels

Tri-axially Braided or Stitched Fabric Preforms





Solvent Extraction



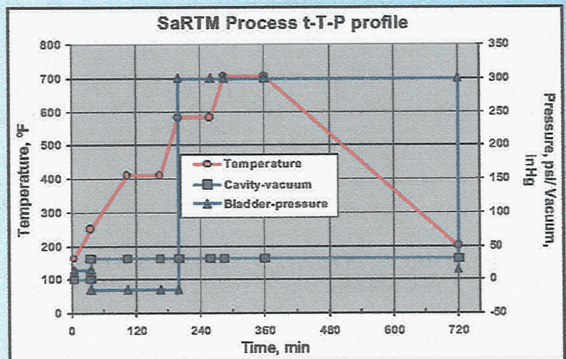
Consolidation

C-scan

Post Cure Cycle

- RT to 450°F in 2h, hold for 1 hr;
- 450 to 550°F in 2 h, hold for 1h;
- 550 to 600°F in 2 h, hold for 2;
- 600 to 700°F in 2h, hold for 16 h;
- Cool to RT in Oven (for 4 hrs)

Drying C-scan



FIBER ARCHITECTURE: PROCESSING

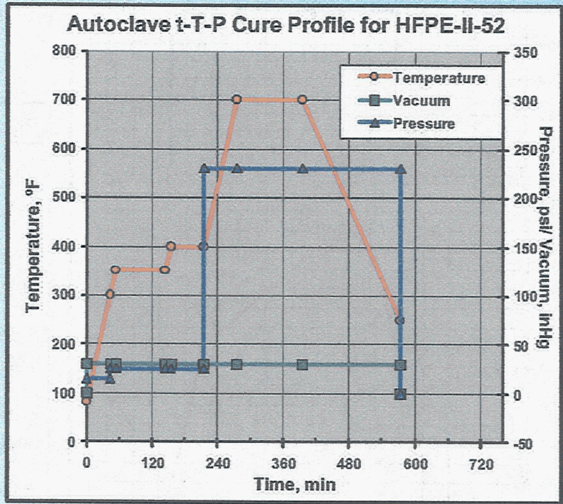
HFPE-II-52 resin

- Stitched Uni-Fabric Composite Panels

Stitched Fabric Preforms
⇓
Laying-up/Bagging

↓

Resin Film Infusion cycled through 200-350°F with pressure
⇓
Vacuum Bagging



C-scan

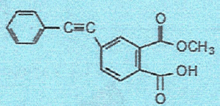
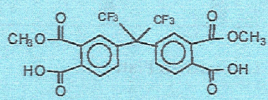
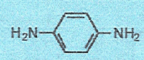
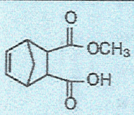
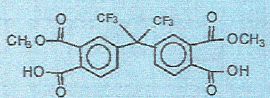
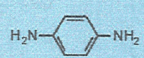
Drying

Post Cure Cycle

- RT to 450°F in 1h, hold for 1 hr;
- 450 to 700°F in 6h, hold for 16 h;
- Cool to RT in Oven (for 4 hrs)

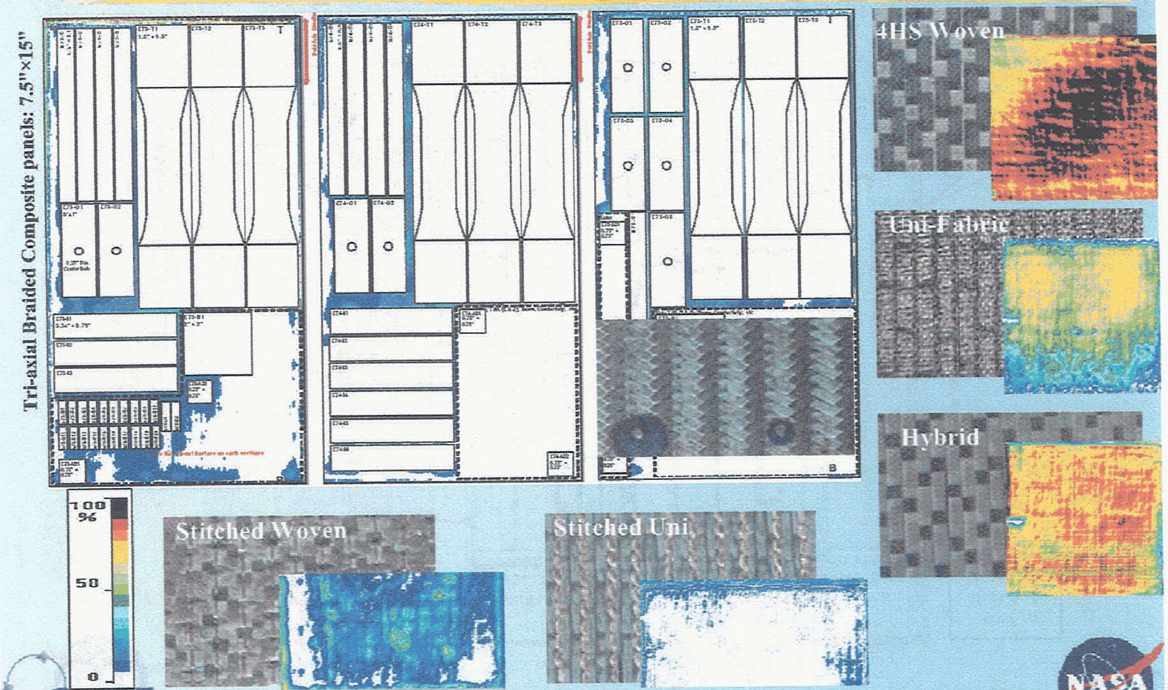
C-scan

FIBER ARCHITECTURE: PROCESSING

	Endcap	Dimethyl Ester	Diamine	Repeat Unit(n)
Molar Ratio	2	n	n+1	
HFPE	 PEPE	 HFDE	 *p*-PDA	9
PMR-II-50	 NE	 HFDE	 *p*-PDA	9

Ref: 1. Kathy C. Chuang, Joseph E. Waters, Int'l SAMPE Symposium, 40, 1113 (1995)
2. Kathy C. Chuang, Demetrio S. Papadopulous, Cory P. Arendt, Int'l SAMPE Symposium, 47, 1175 (2002)

FIBER ARCHITECTURE: TEST PANELS

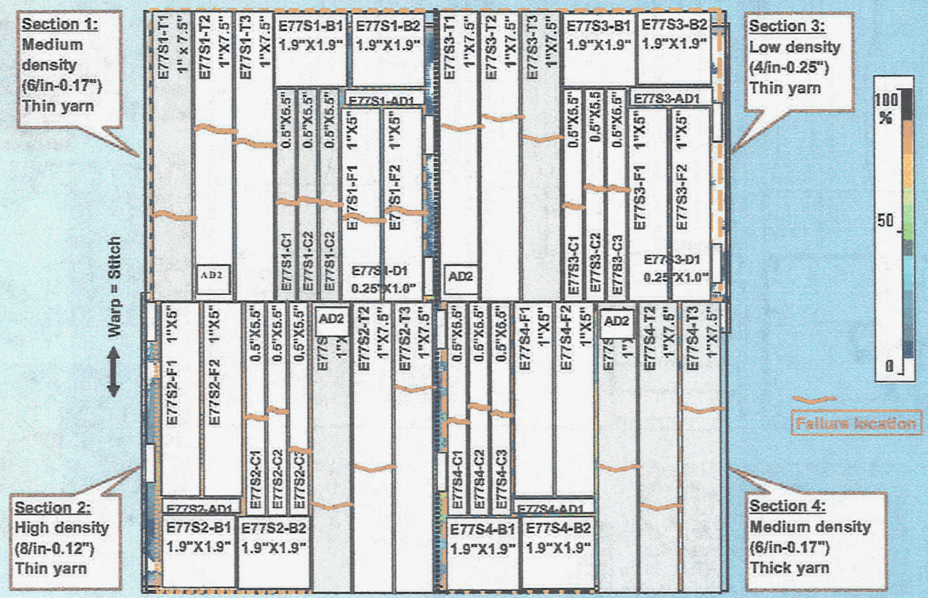


STITCHING OPTIMIZATION: VARIATION

- Stitching --- Excellent blistering stopper, but at the expense of the in-plane mechanical properties?
- Stitching Options with 4HS Woven Fabric
  - Stitch density; 4 : 6 : 8 stitches per inch
  - Stitch-line spacing; 0.12" : 0.17" : 0.25"
  - Stitching yarn size (S2 glass); thin (150 1/0) : thick (150 1/2)
- Properties Evaluated
  - Tension, Compression, and Flexure
  - Void content, FVF, T_g, T_d, CoTE
  - Hygrothermal Blistering Test
    - Fully saturated
    - 20 & 50 °C/min heating

STITCHING OPTIMIZATION: TEST MATRIX

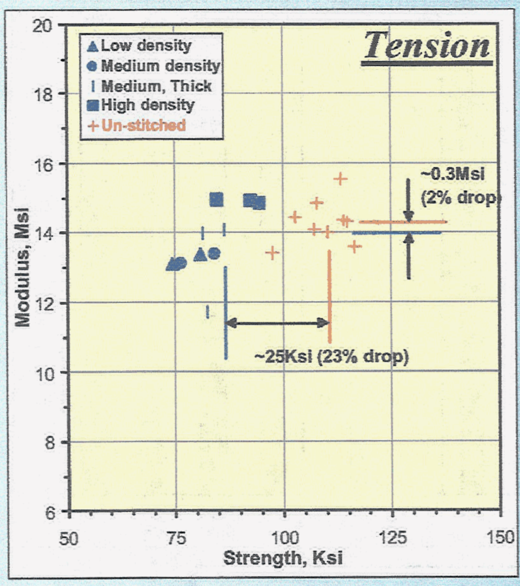
- 15"x15"x0.1" 4HS M40JB/PMR-II-50 Trial Panel w/ four stitching pattern combinations

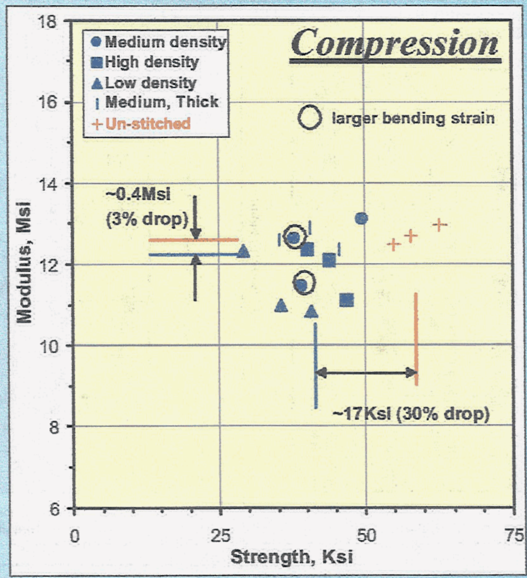


STITCHING OPTIMIZATION: TEST RESULTS

Stitch Pattern	FVF, %
Low Density Thin Yarn; 4 stitches/in; 0.25" spacing	53 ± 0.4
Medium Density 1 Thin Yarn; 6 stitches/in; 0.17" spacing	57 ± 0.5
Medium Density 2 Thick Yarn; 6 stitches/in; 0.17" spacing	60 ± 0.4
High Density Thin Yarn; 8 stitches/in; 0.12" spacing	59 ± 1.1

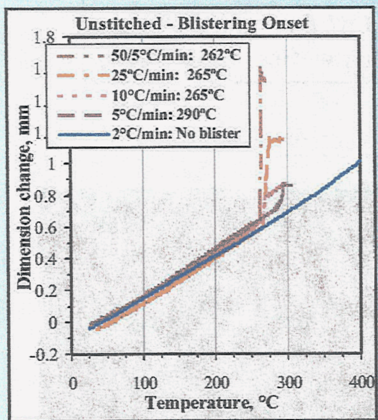
STITCHING OPTIMIZATION: TEST RESULTS

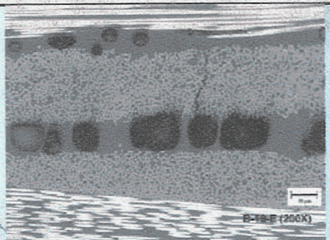




Note: 1. Stitched panels by SaRTM @ 300psi vs. Un-stitched by Hot-press @ 500psi
2. Stitched samples tested @ 0.5in/min vs. Un-stitched @ 0.05in/min

STITCHING OPTIMIZATION: TEST RESULTS



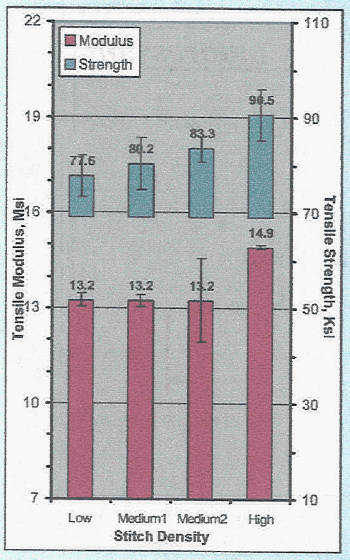


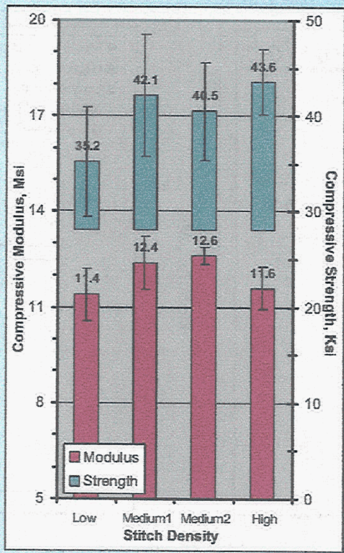
Blistering Resistance

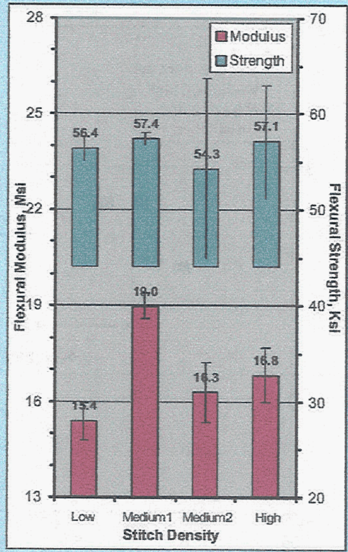
Stitch Density	Void Cont. %	Moisture Uptake, %	Blister Onset, °C	
			Rate 1*	Rate 2**
Un-stitched	2.3 ± 0.4	1.47	262	N/A
Low	5.8 ± 0.1	1.74	None	280
Medium 1	4.9 ± 1.2	1.74	None	None
Medium 2; thick yarn	4.6 ± 0.1	1.64	None	310
High	3.6 ± 0.5	1.63	None	N/A

* Heating Rate 1: 50°C/min to 250°C ⇒ 5°C/min to 400°C
** Heating Rate 2: 50°C/min to 400°C

STITCHING OPTIMIZATION: TEST RESULTS





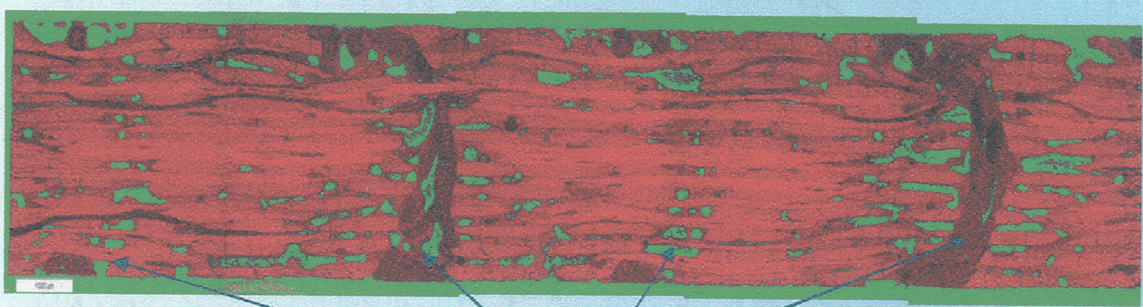


"Medium 1" w/ thin yarn was selected for:
Better Compressive & Flexural Performance, and Blistering Resistance

STITCHING: TRANSVERSE PROPERTIES

M40JB Uni-fabric $[0/90]_{6S}$/HFPE-II-52 Composite Panel w/ Boeing Stitching (40 penetration/in^2; 5 stitches/in – 1/8 spacing by Lock-stitch w/ fiber glass yarn)

Typical Cross-Section normal to Stitch Direction



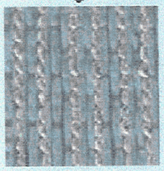
Transverse Direction

Stitch Lines

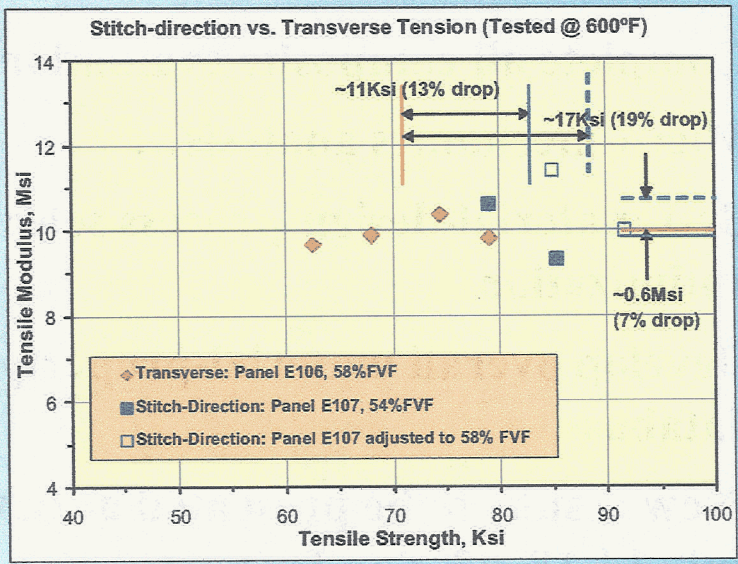
~ 0.11" Thick;
4.0±0.5% Void Content;
58±1.5% F.V.F

STITCHING: TRANSVERSE PROPERTIES

Stitch-direction



Transverse



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SUMMARY & CONCLUSIONS

- Studied six representative fiber architectures, optimized design and process, completed test panel fabrication and test specimen preparation
  - Testing underway…
- Selected the medium density w/ thin yarn as the optimum stitching pattern based on mechanical properties and blistering performance,
- Resulted in-plane property degradation of stitched panel; 2~3% in modulus but 20~30% in strength in both tension and compression,
- Transverse property degradation in stitched panel; 15~20% tensile strength drop due to:
  - array formation of the stitch-induced damage normal to transverse direction?

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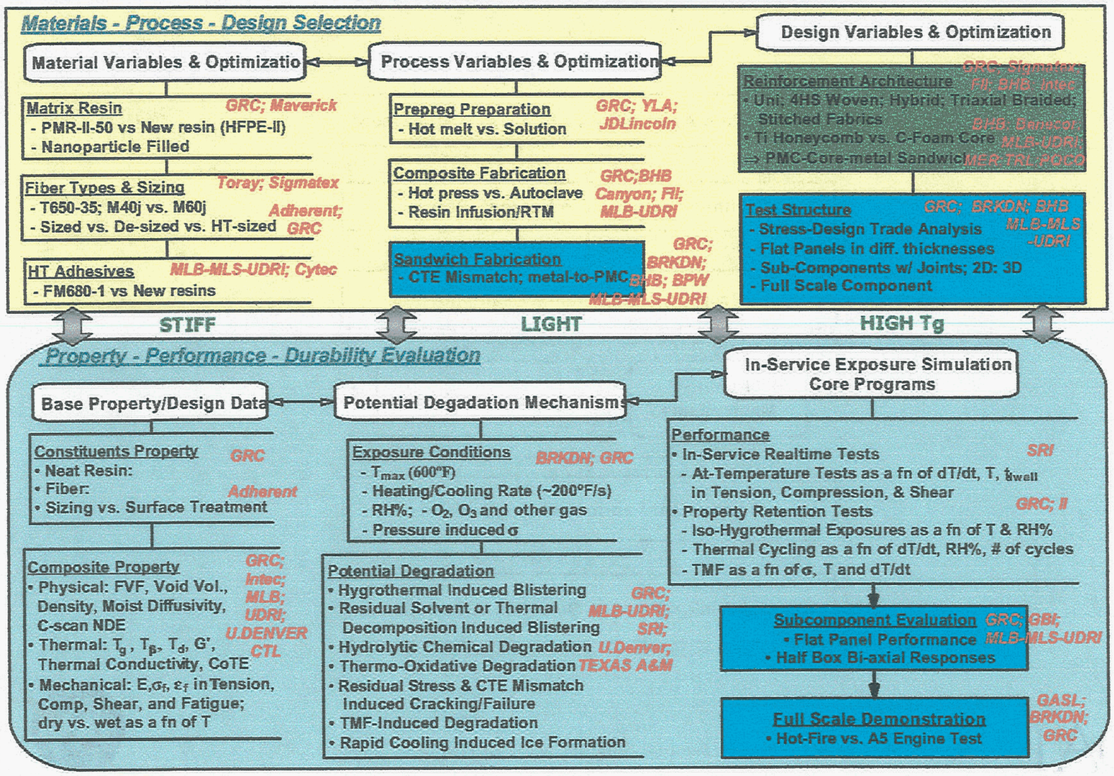
Continuing Work Plans

- Complete all composite evaluation tests…
- Micro-mechanics analysis…
- Best material-design-process selection and optimization
- Develop overall material-property database
- New results to be presented at ICCM-14, July 14-18, 03, San Diego, CA.

Acknowledgement

- Maverick Corp.; PMR-II-50 resin
- Joe Lavelle & Tim Ubienski; test specimen preparation for stitch optimization
- David Hull, GRC; OM microscopy

HTPMC for Access to Space Component Development

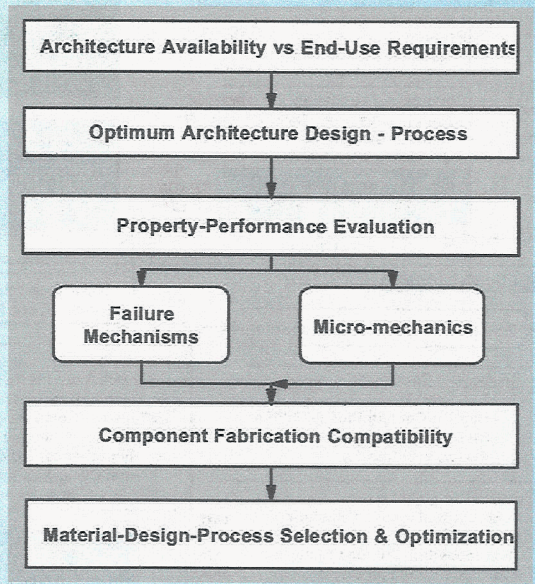


Fiber Architecture: Objectives

- Evaluate PMC materials and generate database as a function of fiber reinforcement architecture for temperature-moisture-stress-high heating rate Aeropropulsion applications

- Optimize design and fabrication processes

FIBER ARCHITECTURE: WORK PLAN



FIBER ARCHITECTURE: TEST MATRIX

TEST TYPE		COMPOSITE PANEL TYPE (PMR-II-50/M40JB): FIBER ARCHITECTURE					
		4HS WOVEN FABRIC	UNI-TAPE CROSS-PLY	UNI-WOVEN HYBRID	TRIAXIAL BRAID	STITCHED UNI-TAPE	STITCHED 4HS WOVEN
PROPERTIES	CONDITIONS						
Compression (3 repeats)	Dry RT	• 12-ply fabric; $[0_f,90_f,90_f,0_f,0_f,90_f]_{1s}$ ~0.1" TH	• 24-ply uni; $[0,90,90,0,90,0,0,90,0,90,90,0]_{1s}$ ~0.1" TH	• 8-ply fabric + 8-ply uni; $[0_f,90,0,90_f,0_f,0,90,0,90_f]_{1s}$ ~0.1" TH	• Equivalent to 12-ply fabric, . By SaRTM ~0.1" TH	• 24-ply uni; $[0,90]_{6s}$; . HFPE-II-52 resin By RFI ~0.11"TH	• 12-ply fabric; $[0_f,90_f,90_f,0_f,0_f,90_f]_{1s}$ By SaRTM ~0.11" TH
	Dry T_{max} (600°F)						
	Wet T_{max} (600°F)						
Open Hole Comp/Northrop (3 repeats)	Dry RT						
	Dry T_{max} (600°F)						
	Wet T_{max} (600°F)						
Tension (3 repeats)	Dry RT	• 2-; $[0_f]_{1s}$, 0.02"TH • 4-;$[0_f,90_f]_{1s}$, 0.033" • 12-ply fabric	• 4-; $[0,90]_{1s}$, 0.02" • 8-; $[0,90,90,0]_{1s}$, ~0.035" TH • 24-ply uni	• 8/8 fabric/uni; • 2/4 fabric/uni; $[0_f,90,0]_{1s}$; ~0.035" TH			
	Dry T_{max} (600°F)						
	Wet T_{max} (600°F)						
SBS (6 repeats)	Dry RT	• 12-ply fabric	• 24-ply uni	• 8-ply fabric + 8-ply uni			
	Dry T_{max} (600°F)						
	Wet T_{max} (600°F)						
In-plane Shear (Iosipescu) (3 repeats)	Dry RT						
	Dry T_{max} (600°F)						
	Wet T_{max} (600°F)						
DMA	RT to 500°C						
TMA (both X & Z)	RT to 500°C						
TGA	RT to 800°C						
Thermal Cond.	RT to T_{max} (600°F)						
Moisture Diff.	RT to 80°F	2, 4, 6, 8, & 12-ply fabric	4, 8 and 24-ply uni	• 8/8 fabric/uni • 2/4 fabric/uni			
Blistering (Fully Saturated)	2"×2" coupon						
	12"×12" panel						
Hygrothermal Rapid heat-up Cycle (w/ 12"×12" panel), 1 - 200 cycles		Selected Architecture Systems Only					

• 6-; $[0_f,90_f,0_f]_{1s}$, 0.052"TH
• 8-; $[0_f,90_f,90_f,0_f]_{1s}$, 0.065"TH

~108 g/m² FAW per layer w/ 6K M40J C-fiber